Urbanization-Induced Land and Aerosol Impacts on Storm Propagation and Hail Characteristics

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ABSTRACT: Changes in land surface and aerosol characteristics from urbanization can affect dynamic and microphysical properties of severe storms, thus affecting hazardous weather events resulting from these storms such as hail and tornadoes. We examine the joint and individual effects of urban land and anthropogenic aerosols of Kansas City on a severe convective storm observed during the 2015 Plains Elevated Convection At Night (PECAN) field campaign, focusing on storm evolution, convective intensity, and hail characteristics. The simulations are carried out at the cloud-resolving scale (1 km) using a version of WRF-Chem in which the spectral-bin microphysics (SBM) is coupled with the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC). It is found that the urban land effect of Kansas City initiated a much stronger convective cell and the storm got further intensified when interacting with stronger turbulence induced by the urban land. The urban land effect also changed the storm path by diverting the storm toward the city, mainly resulting from enhanced urban land-induced convergence in the urban area and around the urban–rural boundaries. The joint effect of urban land and anthropogenic aerosols enhances occurrences of both severe hail and significant severe hail by −20% by enhancing hail formation and growth from riming. Overall the urban land effect on convective intensity and hail is relatively larger than the anthropogenic aerosol effect, but the joint effect is more notable than either of the individual effects, emphasizing the importance of considering both effects in evaluating urbanization effects.

KEYWORDS: Atmosphere-land interaction; Clouds; Convection; Turbulence; Cloud microphysics; Hail

1. Introduction

Urbanization is an extreme case of land-use change (Shepherd 2005), along with intensive anthropogenic aerosol emissions. Worldwide urban land and population have grown rapidly over the twentieth century. All regions are expected to urbanize further during the coming decades (Alig et al. 2004). In the United States, urban land is projected to increase from 39.5 million ha in 1997 to 70.5 million ha in 2025 (Alig et al. 2004). Urbanization has significant local impacts on weather and climate based on the National Climate Assessment (Brown et al. 2014), including studies of Baker et al. (2002), Grimmond (2007), Hallett and Corfee-Morlot (2011), and Rosenzweig et al. (2010), etc. The majority of past studies related to the impacts of urbanization on weather have focused on temperature (e.g., Kalnay and Cai 2003; Hale et al. 2008) and precipitation (e.g., Shepherd 2005; Kaufmann et al. 2007; Kishtawal et al. 2010; Han et al. 2014; Liu and Niyogi 2019). There is a lack of studies examining impacts on severe convective storms that produce large hail, tornadoes, and damaging winds, which cause as much annual property damage and more deaths than hurricanes in the United States based on National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center (2012). Hail produces roughly 60% of the annual average losses in the United States, compared to 20% for both damaging wind and tornadoes (Gunturi and Tippett 2017). Understanding physical factors impacting hail occurrences is important to improve hail prediction and mitigate its impact.

Urbanization could impact storm properties through the following two major pathways. The first major pathway is through changes in land surface conditions. For urban land, the most typical and extensively studied effect is the increase of surface temperature compared to the surrounding rural area, known as the urban heat island (UHI) effect (e.g., Bornstein and Lin 2000; Shepherd et al. 2002; Shepherd 2005; Hubbart et al. 2014). Convective storms may be initiated at the UHI convergence zone that is created through a combination of increased temperature and mechanical turbulence resulting from complex urban surface geometry and roughness (Bornstein and Lin 2000; Shepherd 2005; Hubbart et al. 2014; Liu and Niyogi 2019). Urban landscapes can impact sensible and latent heat flux, soil moisture, etc., affecting thunderstorm initiation with a higher frequency in urban land and its downwind area (Haberlie et al. 2015) and changing the location and amount of precipitation compared to preurbanization (Shepherd et al. 2002; Niyogi et al. 2011). In
addition, urban land use can modify the propagation of storm systems passing over/through urban areas. For example, Loose and Bornstein (1977) found that frontal systems retarded over the upwind half of the city but accelerated over its downwind half because of changes in horizontal pressure gradients associated with UHI. Both observational analysis and modeling studies suggested that moving thunderstorms tended to bifurcate and move around the city because of the urban barrier effect (Bornstein and Lin 2000; Guo et al. 2006). Satellite analysis of Shepherd (2005) showed that summer monsoon storms forming in the mountains east of Phoenix often propagated westward toward the city. The second major pathway for the urbanization impacts is through pollutant aerosols associated with industrial and population growth in cities. Previous studies showed that urban aerosols invigorate precipitation in urban downwind regions through aerosol–cloud interactions (ACI; e.g., van den Heever and Cotton 2007; Carrió and Cotton 2011; Fan et al. 2018). A recent study showed aerosol spatial variability in the Seoul area may play an important role in a torrential rain event (Lee et al. 2018). Past studies showed aerosols can invigorate deep convective clouds and precipitation through (i) enhanced latent heating in ice-related processes, which is induced by freezing of a larger amount of cloud drop surface area resulting from the formation of a larger number of small droplets (so-called warm-phase invigoration; e.g., Fan et al. 2007, 2018; Sheffield et al. 2015; Lebo 2018). The WRF-Chem-SBM model is very computationally expensive but provides more physically representative cloud microphysics and aerosol–cloud interactions (Gao et al. 2016) than the original WRF-Chem model. The severe convective storm event simulated in this study occurred on 1–2 July 2015 in Kansas and Missouri and was observed during the 2015 Plains Elevated Convection At Night (PECAN) field campaign (Geerts et al. 2017). This severe convective storm produced significant severe hailstones, a series of tornadoes, and strong winds. Sensitivity tests are carried out based on a baseline simulation of the case to evaluate the joint and individual effects of urban land and anthropogenic aerosol on storm development and hailstone properties near Kansas City, Missouri. The impact on tornado potential will be presented in a follow-on paper.

2. Case description and observations

The severe convective storm case selected for this study occurred on 1–2 July 2015. The convection initiated northwest of and translated over Kansas City. The nearest operational NEXRAD weather radar is KEAX based in Kansas City, which observed the development of the convective system (Figs. 1a–c). Clear distinctive characteristics of supercellular convection were observed such as an extensive hook echo (Figs. 1b,c) and mesocyclone (black box in Figs. 1d and 1e) between 2300 UTC 1 and 0100 UTC 2 July. The storm subsequently grew upscale into a mesoscale convective system with a leading stratiform rain region as described in Cui et al. (2019). The hook echo structure of the supercell storm was initially identified at ~2330 UTC and the maximum reflectivity reached about 56 dBZ at that time. An EF0 tornado was initially observed at 2333 UTC in Kansas City and there were 6 tornado reports in total between 2300 UTC 1 and 0400 UTC 2 July based on the NOAA Storm Prediction Center (SPC) (Fig. 1f). Hailstones up to 3 in. (1 in. = 2.54 cm) in diameter were reported by SPC and wind gusts exceeded 74 miles per hour (1 mph ≈ 0.45 m s⁻¹) were observed over a large area (Fig. 1f). Limited hailstone reports are probably because of the local nighttime and the low population density after passing over Kansas City.

The tornadic supercell storm developed within a synoptic-scale environment favorable for storm formation and maintenance. Data from the North American Regional Reanalysis...
NARR reanalysis at 1800 UTC 1 July 2015 are presented to highlight characteristics of the synoptic-scale condition (Fig. 2). The storm formed east of the short-wave trough located in Nebraska (Fig. 2a). The 500 hPa winds exhibit a strong jet stream and upper-level disturbance over Kansas. A surface stationary front stretched from Pennsylvania to a broad region of low pressure in Kansas (Fig. 2b). Surface convergence formed along the stationary front in north Kansas near this time. At 850 hPa, moderate southerly and southwesterly flow east of this low pressure advected warm, moist air northward into Kansas and Missouri \( (12 \text{ m s}^{-1}; \text{Fig. 2c}) \). This warm, moist air led to an unstable environment with convective available potential energy \((\text{CAPE})\) of 3826 J kg\(^{-1}\) and limited convective inhibition \((\text{CIN})\) of \(66 \text{ J kg}^{-1}\) at 1800 UTC based on the NARR data (Fig. 2e; unfortunately, no observed sounding data near the convective initiation were available from PECAN). A cyclonic wind field was formed over the Kansas City region; therefore the low-level wind was southwesterly in the southwest region of Kansas City while southerly in the south and southeast region of the city (Fig. 2d).

The observational data used to evaluate model simulations include the Next Generation Weather Radar (NEXRAD) WSR-88D 3D reflectivity and retrieved precipitation rate. The hail and tornado reports are from NOAA SPC. Another hail dataset is the radar-retrieved maximum expected size of hail (MESH), which is obtained with a newly improved algorithm from Murillo and Homeyer (2019) applied to merged multi-radar observations from the NEXRAD network (Homeyer and Bowman 2017). The GridRad dataset, which is the merged radar reflectivity data from 125 National Weather Service NEXRAD WSR-88D weather radars, has a horizontal resolution of \(0.02^\circ \times 0.02^\circ\) (about \(2 \text{ km} \times 2 \text{ km}\)) and is available at a 5-min frequency. MESH provides more reliable and coherent spatiotemporal coverage than ground-based reports (Lukach et al. 2017). However, due to the uncertainties relating to radar observables to hail characteristics, it can have large biases in terms of the estimated hailstone sizes (Ortega et al. 2009, 2016). This MESH dataset is estimated to have an uncertainty of \(\pm 7 \text{ mm}\) (Zhang et al. 2019).

The precipitation datasets are from the NCEP 4-km Gridded Data (GRIB) stage IV data (Lin 2011) and the sounding data at the TOP site included mandatory and significant levels and are obtained from the standard stations available at the website of University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

3. Model and experimental design

The WRF-Chem-SBM model used in this study is based on the development of Gao et al. (2016), with updates in both WRF-Chem (Grell et al. 2005; Skamarock et al. 2008) and SBM (Khain et al. 2004; Fan et al. 2012). WRF-Chem was
updated to version 3.9.1 for this study. Following Gao et al. (2016) where the model was applied to a warm stratocumulus cloud case, this model is at the first time applied to a severe convective storm case in this work. The coupled fast version of SBM was updated to include the hail option as used in Fan et al. (2017) and Han et al. (2019), which is also the option used for this study. As detailed in Gao et al. (2016), the SBM is currently coupled with the four-sector version of MOSAIC (Fast et al. 2006; Zaveri et al. 2008). Besides improved representations of cloud microphysical processes compared with the original WRF-Chem with a two-moment bulk microphysics implementation, some aerosol processes are changed, including aerosol activation, resuspension, and in-cloud wet removal. With this model, both aerosol and cloud processes can be more realistically simulated, particularly under the condition of complicated aerosol compositions and spatial heterogeneity, and both aerosol–radiation and aerosol–cloud interactions are considered (Gao et al. 2016).

The multilayer urban canopy model BEP (Martilli et al. 2002; Salamanca and Martilli 2010) coupled with BEM scheme is chosen for urban parameterization. The BEP + BEM parameterizations take into account the energy exchange between the atmosphere and the interior of a building and represent one of the most sophisticated urban schemes. They have been evaluated and applied to many studies associated with urbanization effects (e.g., Misnis and Zhang 2010; Flagg and Taylor 2011; Liao et al. 2014). Other physics schemes used for the model simulations include the Rapid Radiative Transfer Model for GCMs (RRTMG) shortwave (SW) and longwave (LW) radiation schemes (Iacono et al. 2008), the Noah land surface model (Chen and Dudhia 2001), and the Mellor–Yamada–Janjić (MYJ) planetary boundary layer scheme (Mellor and Yamada 1982; Janjić 2001).

The dynamic core of WRF-Chem-SBM is the Advanced Research WRF Model that is fully compressible and non-hydrostatic with a terrain-following hydrostatic pressure
vertical coordinate. The grid staggering is the Arakawa C grid. The model uses the Runge–Kutta third-order time integration schemes, and the third- and fifth-order advection schemes are selected for the vertical and horizontal dimensions, respectively. The positive-definite option is employed for the advection of moist and scalar variables. The model uses a time-split small step for acoustic modes.

Table 1 summarizes the major simulations that are carried out for this study. The baseline simulation of the observed storm case is referred to as “UlandAero” in which both urban land and anthropogenic aerosol effects are considered. Based on UlandAero, several sensitivity tests are performed to investigate the combined and individual effects of urban land and anthropogenic aerosol. In No_UlandAero, the urban land surface is replaced by the surrounding cropland but the anthropogenic emissions are still on; while in No_Aero, the urban land is kept but the anthropogenic emissions are turned off. The effect of urban land is obtained by comparing UlandAero with No_ULand, therefore, the urban land effect is considered under the polluted aerosol condition (i.e., anthropogenic emissions are on). The effect of anthropogenic aerosols is investigated by comparing UlandAero with No_Aero, meaning under the condition of urban land condition. The joint effect of both urban effect and anthropogenic aerosols is obtained by comparing UlandAero with No_UlandAero.

The initial and boundary conditions used to drive the real-case simulations are produced from the High-Resolution Rapid Refresh (HRRR) analysis data. HRRR incorporates advanced data assimilation with high-resolution radar observations and the data have a 3-km horizontal grid spacing. The simulations are configured with a domain (Fig. 2f) consisting of 700 × 600 grid points with a horizontal grid spacing of 1 km and 41 vertical levels with a grid spacing of ∼20 m at the lowest levels and ∼800 m at the model top. The dynamic time step is 5 s. The baseline simulation starts at 0000 UTC 30 June and is run for 36 h to allow chemistry spinup, using the meteorological fields from HRRR analysis data for initial and boundary meteorological conditions and the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), for initial and boundary conditions of gas-phase species and aerosols. Finally, the simulation is reinitialized at 1200 UTC 1 July using the meteorological conditions from HRRR (the chemical fields are from the previous spinup run at the same time step), and run for 18 h. All the sensitivity simulations described above start from 1200 UTC 1 July with the same initial and boundary conditions for both meteorology and gases/aerosols. The model output frequency for dynamics and microphysics fields are every 10 min.

Anthropogenic emissions are obtained from the U.S. Environment Protection Agency (EPA) National Emission Inventory (NEI) with a 4 km × 4 km horizontal resolution using the year 2011 rates. Biogenic emissions are obtained from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) with a monthly temporal and 1-km horizontal resolution (Guenther et al. 2012). The Fire Inventory from NCAR (FINN) program (Wiedinmyer et al. 2011) is used to generate daily, 1-km resolution biomass burning emissions. Due to the 33-bin version of SBM in which the maximum size bin for hail is 0.67 cm, we were not able to use the SBM to directly simulate the hailstone of 1 in. and larger. Thus, a physically based hail forecasting model (HAILCAST) is integrated into the simulations to estimate the maximal hail size reaching the ground surface (Adams-Selin and Ziegler 2016; Adams-Selin et al. 2019). HAILCAST forecasts the maximum expected hail diameter at the surface using updraft and microphysics information produced by simulations. The most updated HAILCAST version from WRF v4.0 (Adams-Selin et al. 2019) was incorporated into the WRF-Chem v3.9.1 for this study.

4. Results

a. Model evaluation

The simulated 1–2 July PECAN storm is evaluated in radar reflectivity, rain rate, and the associated thermodynamic environment in the baseline simulation ULandAero here (Figs. 3 and 4). The overall storm structure is simulated well, as shown from the spatial distribution of the composite radar reflectivity at its peak time (Figs. 3a, b). The model obviously overestimates radar reflectivity. The probability distribution function (PDF) of simulated reflectivity frequency shows a shift to higher values than NEXRAD, with a large overprediction (by ∼5 times) of the frequencies of moderate reflectivity values of 35–45 dBZ (Fig. 3c). The PDF of simulated precipitation rates has a similar shift as the radar reflectivity, with the simulated frequency of moderate rain rates (5–15 mm h⁻¹) largely overestimated (by ∼2 times; Fig. 3d). The temporal evolution of the storm’s precipitation is well captured in simulations (Fig. 4a). However, the mean precipitation rate is overestimated mainly due to the overprediction of the frequencies of rain rates of 5–30 mm h⁻¹ (Figs. 3d and 4a).
The factors leading to the model's overestimation of precipitation rate and reflectivity were examined. It was found that the simulated storm occurs in a much more humid environment than the real-world situation. The water vapor mixing ratio at low levels below 2 km above ground level (AGL) in the baseline simulation (ULandAero) is up to 4 g kg$^{-1}$ larger than the sounding measurement at 0000 UTC 2 July when the storm initiated (Fig. 4c). The relative humidity (RH) is generally 60%–70% below 1 km AGL in ULandAero, while the observed value is only about 40%–50% in general (Fig. 4d). The overestimation of low-level moisture in our simulation mainly results from the HRRR analysis data used to drive the simulation, as the water vapor mixing ratio from ULandAero is similar to HRRR (Fig. 4c). The RH in HRRR is even higher than ULandAero because of lower temperatures (Figs. 4b,d).

The higher moisture could lead to a more unstable atmosphere. The corresponding CAPE from ULandAero (HRRR) is about 3953 (3870) J kg$^{-1}$, a few times higher than 893 J kg$^{-1}$ measured by the sounding. Stronger convection and more precipitation would be produced due to the high moisture bias. Since 1) it is rather difficult to adjust moisture in real-case simulation, because every grid point over the domain is initiated with a different value and influenced by the boundary conditions differently, and there is large spatial variability, and 2) reducing biases in HRRR data is beyond the scope of the work, we are not able to further improve our simulations. However, we anticipate this model bias would not qualitatively affect our key conclusions about urbanization effects since the supercell storm structure and propagation is well simulated (i.e., the storm type is not different).

Worth mentioning is that the large overestimation of reflectivity has been commonly found in previous studies, which can be partly the result of crude Rayleigh scattering assumptions applied to the model calculation. For example, the reflectivity for ice particles may follow something close to $D^{-4}$ instead of $D^{-6}$ (Ryzhkov and Zrnić 2019). With the SBM, it can also be contributed by a few largest bins with size larger than 2000 m

Figures 3c, 3d, and 4a also show that precipitation and radar reflectivity from this tornadic supercell storm are not affected much by either urban land cover or anthropogenic aerosols. The aerosol effect on precipitation and reflectivity is expected to be small because of the high background aerosol concentrations (more than 1000 cm$^{-3}$) and the relatively small contrast of aerosol concentration between rural and urban regions, in comparison with the regions like Houston where the aerosol effect is found to be large (Fan et al. 2020). The aerosol concentration near the surface over the urban area is only about 2–3 times higher than over the rural area on average and the difference decreases quickly as the altitude increases (Fig. S2).
The relatively high aerosol concentrations from lateral boundaries might also contribute to the small effect of aerosols from urban emissions (Fig. S2).

b. Effects on storm initiation and propagation

We start from the storm initiation and propagation. As shown in Figs. 5 and 6, there are two distinct groups of results: ULandAero and No_Aero in which the urban land effect is considered have similar results in storm initiation and propagation, which are very different from those in No_ULand and No_ULandAero in which the urban land is replaced by the surrounding cropland. This suggests that the urban land effect produces a notable effect on storm initiation (Fig. 5) and the propagation path (Fig. 6) while the anthropogenic aerosols do not affect them. The simulated storm propagation path with the urban land effect considered (i.e., ULandAero and No_Aero) is in better agreement with observation compared with those in No_ULand and No_ULandAero in which the urban land effect is removed. The similar storm paths between No_ULand and No_ULandAero as well as between ULandAero and No_Aero in Figs. 5 and 6 means anthropogenic aerosols do not have a considerable effect on the storm initiation and propagation path in this case, independent of land-cover types.

The two simulations that include the urban land effect (ULandAero and No_Aero) initiate a larger cloud northwest of Kansas City at 2120 UTC (black ovals in Figs. 5a and 5d) compared with those in No_ULand and No_ULandAero in which the urban land effect is removed. The storms develop and move southeastward, and those with the urban land effect appear larger. We do notice that by 2210 UTC (right column in Fig. 5), No_ULand and No_Aero have developed similar cells and their cloud fields are starting to look more similar. This is because the urban land effect on storm initiation dampens with time. However, even at this time, 30 min after initiation, No_Aero with the urban land effect continues to produce more column-integrated hydrometeor condensate than do the simulation without this effect (No_ULand).

To explain how the urban land leads to a stronger convection initiation, the dynamics, thermodynamics, and kinematics are
examined in ULandAero and No_ULand at 2120 UTC as shown in Fig. 7. The urban land provides a temperature increase of 2°–3°C at 45 m AGL (lowest model level) over the city as well as over a large area downwind due to the southerly low-level wind resulting in warm air advection (Figs. 7a–c). This temperature increase extends to about 0.7–0.8 km AGL vertically (Figs. 7b,c). Corresponding to the heating in ULandAero, stronger turbulence and upward motion are produced at low levels relative to No_ULand (Fig. 7d, left vs right), particularly over the downwind of the urban area where moisture is higher than the urban area. As a result, a stronger convective cloud is initiated in ULandAero compared with No_ULand. The 2°–3°C-higher temperature at 45 m AGL over the urban and the area downwind results from sensible heat fluxes that are more than 2 times larger over

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**Fig. 5.** Column-integrated hydrometeor condensate content (kg m$^{-2}$) for (a) ULandAero, (b) No_ULandAero, (c) No_ULand, and (d) No_Aero at (left) 2120, (center) 2130, and (right) 2210 UTC 1 Jul. The black ellipse in the left column marks the location of storm initiation. The gray solid (urban land considered) or dashed (urban land replaced) contour lines denote the location of Kansas City.
In No_ULand, there is a lack of boundary layer convection, and a very small cloud is initiated due to the cold front environment over north Kansas between 2200 and 2300 UTC. The stronger turbulence and convection downwind of the urban area in ULandAero compared with No_ULand can be attributed to larger low-level heating and the larger urban–rural land-cover gradient which leads to larger temperature and moisture gradients (color contour in Figs. 7c and 7d) and, subsequently, stronger vertical mixing (line contour in Fig. 7d), which has been discussed in many past studies (e.g., Simpson et al. 2008; Shem and Shepherd 2009; Liu and Niyogi 2019). Here, the moisture gradient between the urban area and its downwind in ULandAero is much

**Fig. 6.** Temporal evolution of storm depicted by the reflectivity of 30 dBZ at 2 km AGL (contour lines) from (a) NEXRAD, (b) ULandAero, (c) No_ULandAero, (d) No_ULand, and (e) No_Aero at the times (UTC) as marked in (a) for observation and (b) for simulations. The dashed red arrow approximates the propagation route of the tornadic supercell, according to the 2 km AGL hook echo marked by red dots. The gray solid (urban land considered) or dashed (urban land replaced) contour lines denote the location of Kansas City.
FIG. 7. (a) Temperature (shading) at 45-m AGL overlaid with the 10-m horizontal wind at 2120 UTC when storm initiates, and vertical cross sections along the lines of AB and CD defined in (a) for (b) $u$-wind vectors, (c) $v$-wind vectors, and (d) water vapor mixing ratio (shading) and vertical velocity (black solid lines are for updrafts with levels of 0.2, 0.3, and 0.4 m s$^{-1}$ and black dashed lines are for downdrafts with levels of $-0.2$, $-0.3$, and $-0.4$ m s$^{-1}$) for (left) ULandAero and (right) No_ULand. The shading in (b) and (c) depicts temperature. Green contours in (a) show the total condensate path of 0.2 kg m$^{-2}$ and in (b)–(d) are the total condensate content of 0.01 g kg$^{-1}$. The purple solid lines at around 200 m in (c) and (d) are used to calculate temperature and moisture gradients from the urban to rural areas. The location of Kansas City is marked by the gray solid and dashed lines in (a) and on the x axis in (b)–(d).
larger than that in No_ULand, whereas the temperature gradient is only slightly larger. For example, at 200 m above the ground from the urban to rural areas, the moisture gradients are 3.6 and 1.8 kg kg$^{-1}$ (100 km)$^{-1}$ in ULandAero and No_ULand, respectively, while the corresponding temperature gradients are 0.95 and 0.83°C (100 km)$^{-1}$. This suggests that the moisture gradient plays a more important role than the temperature gradient. The larger moisture gradient between the urban and downwind area in ULandAero than No_ULand is because of the drying effect from less surface latent heat flux associated with urban land.

**Fig. 8.** Vertical velocity (shading) overlaid with the horizontal wind at 1 km AGL for (left) ULandAero and (right) No_ULand at (a) 2120 UTC when the storm initiates, (b) 2140 UTC when the storm starts to interact with the turbulence, and (c) 2150 and (d) 2330 UTC when the storm further propagates. Green contours in (a) are the total condensate path of 0.2 kg m$^{-2}$ in (a)–(c) and 10 kg m$^{-2}$ in (d). The black parallelograms are the regions for further vertical cross-sectional analysis in Fig. 9. The box positions are adjusted according to storm propagation with time in each simulation.
After the shallow convective cloud is initiated, it further develops and moves southeastward in all simulations. In ULandAero, relatively strong vertical mixing is observed, i.e., convergence–divergence couplets, at different times (left panel of Fig. 8) in the area north of Kansas City where the surface temperature is 2°–3°C higher than the surrounding area. The convective cloud meets with those convergence–divergence couplets at around 2140 UTC, growing into a stronger...

Fig. 9. Vertical cross sections of water vapor mixing ratio (shading) overlaid with updraft velocity (black contour lines) for (left) ULandAero and (right) No_ULand at (a) 2120, (b) 2140, (c) 2150, and (d) 2330 UTC. The updraft contour lines are denoted with the levels of 0.5, 0.75, 1.0, 1.25, and 1.5 m s\(^{-1}\), as labeled in the figure. Green contours denote the total condensate content of 0.01 g kg\(^{-1}\). Water vapor mixing ratios and wind vectors are averaged over the black boxes defined in Fig. 8, and updraft velocities are averaged over the top 25 percentiles (i.e., 75th–100th) of the updrafts (\(>0\) m s\(^{-1}\)) in the same boxes.
As discussed above, the stronger vertical mixing north of Kansas City can be due to the larger sensible heat flux from the urban land as well as the larger urban–rural land-cover gradient around the boundaries. Some past studies have shown that the sensible heat from urban land plays a dominant role in enhancing precipitation (Shimadera et al. 2015). The moisture in the area north of Kansas City is generally lower in ULandAero compared with No_ULand as shown in Fig. 9 (color contours), which does not favor convection; however, the moisture gradient between Kansas City and the north of Kansas City is larger in ULandAero than No_ULand as discussed above. The reasons for the drier air at low levels in the area north of Kansas City in ULandAero compared with No_ULandAero are 1) the southeasterly low-level wind brings in dry air and 2) the urban land of Kansas City further dries it because of the suppressed surface latent heat flux (Figs. 9 and 10d).

Besides the convective intensity, the storm paths start to differ considerably between ULandAero and No_ULand after the interaction of the convective cloud with the turbulence north of Kansas City (Figs. 6 and 8d). The storm is diverted toward the south and passes over Kansas City in ULandAero and No_Aero, while without the urban land effect, the storm passes north of the city (No_ULand and No_ULandAero; Fig. 6). This suggests the urban land-induced convergence in the urban area and at the urban–rural boundaries supports the continued development of the storm toward the city. As a result of the greatly strengthened convective storm by urban land effect, the cold outflow boundary associated with cold pools extends faster toward the south in ULandAero than No_ULand (Fig. 9d). This might be an additional factor enhancing the deviation of the storm path between the two simulations.

The urban land induced turbulence mixing north of Kansas City can be seen as early as 1800 UTC, a couple of hours prior to the convection initiation, when the temperature and moisture differences between ULandAero and No_ULand are first evident (Figs. S4a,b, left). Since the wind direction changes from southeasterly below 0.7 km AGL to southwesterly above it, which makes the area north of Kansas City downwind, the temperature increase is notable (Fig. S4c). Along with the urban–rural land cover gradient which mainly causes a larger moisture gradient, the turbulence mixing is formed similarly as that enhancing the initiation of the storm. In ULandAero with the urban land effect considered, the turbulence mixing becomes stronger with time as the temperature over the area gets higher and the temperature differences between ULandAero and No_ULand are increasing over time (Fig. S4c). By 2140 UTC when the convective cloud approaches the area north of Kansas City, the urban-induced turbulence convection is already quite strong (Fig. 8b, left), thus enhancing the storm development.

It should be noted that the proper choice of a PBL scheme is very important to simulate the turbulence convection induced by the urban land effect and then to correctly simulate the storm initiation location and the propagation path, based on our sensitivity test with another PBL scheme—BouLac (Bougeault and Lacarrere 1989). The reason to test BouLac, which is the only other boundary layer scheme in WRF that can be utilized with BEP + BEM urban parameterization besides MYJ. With BouLac, the temperature increase induced by Kansas City is much smaller than that using MYJ (Fig. S5a), resulting in much weaker turbulence convection over the area north of the city (Fig. S5b). The simulated storm is initialized far more west (farther away from Kansas City; Fig. S5c) compared with MYJ, and the storm propagation path is different (Fig. S5c, purple versus black). The storm initiation and propagation with BouLac do not agree with the observations at all. These results suggest that without the proper simulation of the turbulence convection induced by the urban land effect, the model simulates a storm very different from the observed one. With the MYJ
scheme, we show a good model performance in simulating storm initiation and propagation (Fig. 6 and Fig. S5), which allows us to further investigate the important contribution of the turbulence convection induced by the urban land effect. This also shows the importance of evaluating model simulations before further investigation.

A possible reason for the better performance of MYJ here because MYJ is the best PBL scheme to simulate the boundary layer jet and other PBL structure on clear days based on Wang et al. (2017), and the studied storm was initiated in the clear-sky condition and heavily relied on boundary layer jet transport.

The urban land effects on storm initiation and diverting storm toward the city are consistent with some past observational studies. For example, Haberlie et al. (2015) found a greater convective initiation frequency in the location of downwind of Atlanta, and Shepherd (2005) found that storms forming in the mountains east of Phoenix propagated westward toward the city during summer.

c. Effects on hailstones

The baseline simulation (ULandAero) is first evaluated in the spatial distribution of the maximum hail size over the storm period 2200 UTC 1 July–0500 UTC 2 July. For a fair comparison, a similar method as Adams-Selin and Ziegler (2016) was employed to reproject the 1-km HAILCAST hail data to the 2-km MESH grid, in which the maximum hail size over the 2 × 2 grid points in the WRF HAILCAST data was found and assigned to the 2-km MESH grid point. As stated earlier, the observed storm produced hailstones exceeding the threshold for significant severe hail (diameter of 2 in. or greater). Consistent with the overestimation of radar reflectivity and precipitation, the baseline simulation ULandAero estimates more hailstones and larger hail sizes compared to the observed MESH and SPC reports (Fig. 10). There were only a few hail reports for this case, likely due to low population density and the timing of hail fall (2200–0500 UTC; nighttime locally). The MESH data show a large hail swath near Kansas City, which is much narrower in latitude compared to that simulated by the model. It should be noted that both MESH and the modeled hail data which were calculated by HAILCAST have large uncertainties.

Since other convective storms are occurring and merging in the simulation domain, to examine the joint and respective effects of urban land and anthropogenic aerosols of Kansas City on hail, a cloud tracking algorithm is employed to track the area and movement of the supercell storm passing over Kansas City. The purpose is to accurately account for the hailstones associated with the studied storm as the storm moves by excluding the clouds that are far away from and not affected by Kansas City. The storm tracking algorithm follows...
Feng et al. (2019), which identifies and tracks cloud shield objects with cold cloud brightness temperature (for observation, it is based on the global-merged IR brightness temperature dataset obtained from https://doi.org/10.5067/P4HZB9N27EKU; for simulation, it is converted from the outgoing longwave radiation). The algorithm was adjusted for high resolution (1-km) and high temporal frequency (every 10 min) data; for example, a lower minimum cloud size threshold of 100 km² is used to include small cloud objects, and a larger smoothing window of 60 km is employed to reduce the heterogeneity within cloud compared with the original algorithm. The tracked storms with the cold cloud shield (red curve) and radar reflectivity at 8 km AGL (color contour) are shown in Fig. 11 at different times. The reflectivity inside the cloud shield shows the major precipitating area of the tracked storm. At 0100 UTC (Fig. 11c), some stratiform and low clouds from the left storm in No_ULand and No_Aero merge with the convective cloud near the right bound of the domain. Therefore, they are tracked as one cloud system. But the cloud near the right bound of the domain produces few hailstones, so it would not affect the results of the effects on hailstones. Furthermore, we started tracking the storm from 2200 UTC when hailstones start to form and only tracked the storm until 0130 UTC 2 July for the follow-on analysis of urban land and aerosol impacts on hailstones, because the storm is not much affected by aerosols from Kansas City after that time (after 0130 UTC the aerosols affecting the storm are mainly from the southern part of the domain).

Figure 12 presents the occurrences of HAILCAST-generated severe hail and significant severe hail (SSH) and the joint and respective urban land and aerosol effects on them. With both the urban land and aerosol effects removed (No_ULandAero), the occurrences of both severe hail and SSH are clearly less than ULandAero. The joint effect increases the occurrences of both severe hail and SSH in a similar magnitude (around 20%). The large increase in the occurrence of severe hail is the result of the interactions between the urban land and anthropogenic aerosols, since the individual effect of urban land only increases it by ~5% and the aerosol effect alone even decreases it (Fig. 12b). Therefore, for severe hail, a large nonlinear amplification is seen when the urban land and anthropogenic aerosols interact and work together. For SSH, the joint effect is almost equal to the sum of the individual urban land and anthropogenic aerosol effect. Note that the HAILCAST used in this study calculates hail sizes for the individual grid column, which accounts for the effect of increased updraft speeds but cannot fully account for the effect of increased updraft volumes (Adams-Selin and Ziegler 2016). The hail results shown in this study mainly reflect the effect of updraft speeds. Since both updraft speeds and volumes can play a role in hail growth (Ziegler et al. 1983; Foote 1984; Adams-Selin and Ziegler 2016), we are not able to fully account for the effect of updraft volumes, which might lead to some uncertainties.

The increased occurrences of hailstone events on the ground as a result of the joint effects of urbanization correspond to the increased amount of hail mass and the enlarged hail sizes for the median (4–8 g kg⁻¹) and large (>8 g kg⁻¹) hail mass in the cloud (Figs. 13a,b). The hail number concentrations over those hail mass bins are reduced (Fig. 13c). Indeed, the overall hail number concentration is the lowest in ULandAero among all four simulations, but the hail mass and hail size are the largest, meaning that the urbanization effect increases hailstone occurrences on the ground mainly through producing larger hail in the cloud which can survive from falling through the air, not higher hail number. The individual effect of either factor only increases the hail mass and size for the large mass bin (>8 g kg⁻¹), explaining why the urban land effect or aerosol effect only notably increases the occurrences of SSH as shown in Fig. 12b.
Supercooled droplet properties including mass, number, and size play a key role in hail formation and growth (Khain et al. 2011). Increased occurrences of the large hail mass and increased hail size in the cloud correspond well to the increased supercooled droplet number and mass particularly for the larger quantities (Figs. 13d,e). Supercooled droplet size is slightly reduced, probably because stronger updrafts by the joint effects and individual effect (shown later) enhance droplet nucleation and form much more droplets competing for water vapor. The joint effect on in-cloud hail and supercooled droplet properties is drastically larger compared with either of the individual effect.

The occurrences of updrafts, particularly the strong ones (>20 m s⁻¹; Fig. 14a) increase due to the joint and individual effects. Since the HAILCAST calculation of hail sizes mainly reflects the effect of updraft speeds, not updraft volume, the much-intensified convection should be responsible for the increased hail sizes, because it can increase the supercooled droplet mass and number in the mixed-phase regime by 1) nucleating more droplets, and 2) transporting more droplets from low levels to the supercooled regime (below 0°C). Stronger updrafts are also able to lift and hold larger hail for reentering into cloud updrafts and growing into larger hailstones (Cotton and Anthes 1989; Khain et al. 2011). Therefore, the increased occurrences of strong updrafts (>20 m s⁻¹) may be the first-order factor responsible for the increased occurrences of SSH on the ground by the joint and individual effects of the urban land and anthropogenic aerosols. Note the updraft
occurrence frequencies of different updraft bins as shown in Fig. 14a may reflect the increase of updraft volumes by the joint and individual effects. However, as stated above, our HAILCAST calculation is not able to fully account for the effect of the updraft volumes on hail size. For the anthropogenic aerosol effect, the supercooled droplet mass and number can be increased also by more droplet nucleation and suppression of warm rain processes as suggested from reduced droplet size.

The increased occurrences of these strong-updrafts are reflected by the increased occurrences of thermal buoyancy, particularly the large values (>0.2 m s\(^{-2}\); Fig. 14b). The condensate loading effect which counteracts thermal buoyancy is also increased but the changes are smaller (Fig. 14c), leading to the increased occurrences of net buoyancy (Fig. 14d). The mechanism for the urban land effect to enhance buoyancy and convective intensity has been elaborated in section 4b. As for how the aerosol effect enhances convection, we examine the changes of cold pool intensity from No_Aero to ULandAero following Fan et al. (2017) and found that aerosols weaken it (Fig. S6), which is not favorable to enhance the supercell convection. From the latent heating rates of different cloud microphysical processes, including condensation and ice-related processes (deposition, drop freezing, and riming), there is an increased occurrence of large latent heating rates (>6 K min\(^{-1}\)) from both condensation and ice-related processes by aerosols (Figs. 14e,f). And the increase is larger in the ice-related latent heating than the condensation latent heating. Based on Fan et al. (2018), the same amount of increase in condensation latent heating (lower levels) makes a larger effect on convective intensity than that in ice-related latent heating (higher levels). Thus, the aerosol effects on convective intensity should be because of the latent heating increase from both warm-phase and cold-phase processes in this case.

**Fig. 14.** As in Fig. 13, but for binned (a) updraft velocity, (b) thermal buoyancy acceleration, (c) condensate loading acceleration, (d) net buoyancy acceleration, (e) condensation latent heating rate, and (f) ice-related latent heating rate (sum of deposition, drop freezing, and riming heating). The magenta dashed line represents the actual magnitude of the respective variable from ULandAero, which is denoted by the secondary y axis. The tracking results from simulations with a frequency of 10 min are used.
Overall, the urban land effects on convective intensity, supercooled droplets (including number, mass, and size), as well as occurrences of surface hailstones are relatively larger than the anthropogenic aerosol effects. Although the individual aerosol effects are small, when interacting with the urban land effects, the joint effects on convection, supercooled liquid, and hail occurrences are generally amplified and more notable than any of the individual effects.

Hail formation and growth processes are examined here to understand how the increased supercooled droplet number and mass enhance the hail occurrences. In the fast version SBM used in this study, the hail formation is mainly through the riming of drops by ice/snow particles and drop heterogeneous freezing. The drop heterogeneous freezing is parameterized based on Bigg (1953), which is temperature dependent. From Figs. 15a and 15b, the hail embryo number formation rates from both processes are enhanced by the joint effect and the urban land effect. The aerosol effect only increases the hail embryo formation rates from drop freezing, while does not affect those from riming. However, the hail embryo formation rates from drop freezing are nearly two magnitudes lower than from the riming (x axis of Figs. 15a and 15b) and the occurrences are also about one magnitude smaller (secondary y axis of Figs. 15a and 15b). Thus, hail embryos form predominantly via riming. The joint effect and the urban land effect increase both embryo number and size via riming, whereas the aerosol effect does not affect the embryo number and size that much (Figs. 15a,c).

After hail embryos form, their growth is through riming by collecting supercooled droplets. The riming rates over the different ranges are increased by the joint effect and the urban land effect (Fig. 15d), suggesting that the hail growth is enhanced through stronger riming as a result of larger supercooled droplet number and mass. This shows consistency with the theory of recycling hail into cloud updrafts to grow into larger hail through riming (e.g., Nelson 1983; Tessendorf et al. 2005; Seigel and van den Heever 2013). Stronger updraft speeds by the joint effect and the urban land effect can lift and hold larger hail (Cotton and Anthes 1989; Khain et al. 2011) and increase the chances of recycling hails into updrafts. After reentering the updrafts, more supercooled droplets allow hails to reach larger sizes in the course of recycling (e.g., Ilotoviz et al. 2016, 2018). The anthropogenic aerosol effect increases the occurrences of the large riming rates (>5 g kg⁻¹ min⁻¹; Fig. 15d). Considering the hail embryo number is even slightly reduced by the aerosol effect (Fig. 15a), increased occurrences of the large riming rates mean that on average each hail embryo goes through more times of collecting supercooled droplets to grow into larger hail, explaining the increased occurrences of SSH by the anthropogenic aerosol effect. Aerosols increase the chances of reentering of hail into updrafts through (i) decreasing embryo size and hail size after the previous growth cycle and (ii) increasing updraft speeds and increasing updraft volume that provides more area for the riming to occur.

The aerosol effect on hailstones shown above is the net effect of both ACI and aerosol–radiation interaction (ARI). Additional sensitivity tests are conducted to single out the relative contributions by ACI and ARI. Our results show that occurrences of the significant severe hail increase by 9% and
12% for the aerosol effect with and without ARI, respectively, suggesting that the ACI plays a dominant role in the anthropogenic aerosol effect and the ARI offsets the increasing effect by ACI to some extent (Fig. 12). In other words, ARI reduces the occurrences of SSH. As discussed above, the ACI enhances SSH occurrences through (i) increasing updraft speeds and volume via enhancing latent heating from both condensation and ice-related processes and (ii) increasing supercooled liquid. The reduction in SSH occurrences by ARI might be due to the so-called semidirect effect of absorbing aerosols (e.g., black carbon and dust), which can stabilize the atmosphere by heating and drying low atmosphere (Fan et al. 2008; Koch and Del Genio 2010).

The above analysis also suggests that supercooled droplet number and mass concentrations are the keys for the hail embryo to grow into large hail, not supercooled droplet size.

5. Conclusions and discussion

We have studied how urbanization affects storm development, propagation path, and hailstones through the urban land effect and anthropogenic aerosol effect jointly and respectively for a severe storm occurring during the 2015 PECAN field campaign. This is the first time the WRF-Chem-SBM model has been employed to simulate an observed tornadic supercell storm producing hail, tornado, and strong wind. Extensive evaluations of the baseline simulation with various observations (sounding, radar, precipitation, and hail) show that the model generally captures the observed storm structure, temporal evolution, and propagation. However, the model overestimates reflectivity, precipitation, and the occurrences of hailstones, which should in part be related to a large overestimation of the low-level moisture stemming from the initial and boundary conditions from the HRRR analysis data.

Sensitivity simulations are performed to examine the joint and individual effects of urban land and anthropogenic aerosol on the modeled result. The key results are illustrated in the schematic figure (Fig. 16). It is found that the urban land effect notably changes the storm initiation and propagation path, while the anthropogenic aerosol effect on these characteristics is negligible. With the urban land effect (Fig. 16, left), a stronger convective cell initiates downwind of Kansas City, attributed to stronger turbulence as a result of larger low-level heating and larger urban–rural land-cover gradient. After the convective cloud initiates, it propagates southeastward and is greatly intensified by interacting with stronger turbulence (convergence–divergence couplets) in the area north of the city. The area is also downwind of the city since the wind above 0.7 km AGL is southwesterly and is around the urban–rural boundaries, therefore the stronger turbulence is formed similarly as that enhancing the initiation of the storm. The urban land-induced strong convergence in the urban area and at the urban–rural boundaries diverts the storm toward Kansas City, resulting in a storm passing over the city and ingesting the warm urban plume (dashed black arrow in the left panel of Fig. 16), in contrast with a storm passing to the north of the city when the urban land effect is not considered (Fig. 16, right). The faster propagation of cold pools toward the south associated with strengthened convective storm by the urban land effect could further influence the storm path.

The joint effect of urban land and anthropogenic aerosols enhances the occurrence of severe hail and SSH by ~20%, more notable than either of the individual effects. There is an amplification effect on severe hail from the interaction of the
urban land effect and anthropogenic aerosol effect. The greater abundance of severe hail and SSH as a result of urbanization is because the more intensified storm produces more supercooled droplet number and mass, enhancing hail embryo formation via riming and the subsequent growth by enabling hail embryo experiencing more times of riming growth. Overall, the urban land effect on convective intensity and hail is relatively larger than the anthropogenic aerosol effect, but both individual effects are not large. However, their joint effects amplify the response, emphasizing the importance to consider both effects in evaluating urbanization effects.

For the aerosol impact on hailstones, the major effect is through ACI, which increases latent heating in both condensation and ice-related processes (deposition, riming, and freezing) and thus increases the occurrences of strong convective updrafts. Along with increased droplet number and suppressed warm rain by ACI that lead to more supercooled droplet number and mass, ACI increases the abundance of SSH. However, ARI has the opposite effect, explaining the relatively small net aerosol effect.

A negligible aerosol impact is observed on the supercell morphology and propagation path, consistent with past studies on aerosol impacts on supercells (e.g., Khain et al. 2011; Loftus and Cotton 2014b). The aerosol effect on hailstones revealed here is consistent with the literature studies showing that increasing CCN produced larger hailstones through enhancing supercooled water content and riming growth (e.g., Khain et al. 2011; Ilotoviz et al. 2016). However, Loftus and Cotton (2014b) showed that the increased hail embryo size is the main reason for the enlarged hailstone sizes and they did not see a strong dependence of these large hailstones on riming efficiencies, which is not consistent with the result in Khain et al. (2011). One of the possible reasons for the different results between those studies can be the different treatments in hail formation and growth, particularly the riming process between the models used in the study.

It is worth pointing out that the biases in the simulations of precipitation and hailstones are greater than the differences between the simulations (Figs. 3 and 4a). Thus, the urban land and aerosol effects on them which are obtained from the differences between simulations should be understood within the context of these large modeling biases, suggesting possible large uncertainties in those results.

Overall, we see larger effects on storm properties by the urban land use than the urban aerosols. However, in a similar study for the Houston area where the thunderstorm was developed in a warm and humid environment with weak synoptic forcing and a low background aerosol concentration, we found that the urban aerosol effects on storm intensity and precipitation are much larger than the urban land effect (Fan et al. 2020). Therefore, the relative importance of the urban land effect on storm properties to the urban aerosol effects depends on storm types and associated environmental conditions. We understand the urban land-cover change includes both the surface heat flux change and the surface roughness change. Since the BEP + BEM urban canopy model used in this study considers the building energy effects, changing surface roughness is not a straightforward task and it will also impact energy. Therefore, we are not able to separately look at the contribution from the changes of surface roughness in this study and will be considered in future studies. Since a series of tornadoes were produced from this severe storm, the urbanization effects on tornado potential will be presented in a follow-on paper.

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